

Modeling the VARTM Composite Manufacturing Process

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ABSTRACT

A comprehensive simulation model of the VARTM composite manufacturing process has been developed. For isothermal resin infiltration, the model incorporates submodels which describe cure of the resin and changes in resin viscosity due to cure, resin flow through the reinforcement preform and distribution medium and compaction of the preform during the infiltration. The accuracy of the model was validated by measuring the flow patterns during resin infiltration of flat preforms. The modeling software was used to evaluate the effects of the distribution medium on resin infiltration of a flat preform. Different distribution medium configurations were examined using the model and the results were compared with data collected during resin infiltration of a carbon fabric preform. The results of the simulations show that the approach used to model the distribution medium can significantly effect the predicted resin infiltration times. Resin infiltration into the preform can be accurately predicted only when the distribution medium is modeled correctly.

KEY WORDS: Composite Materials, Flow Modeling, VARTM

1. INTRODUCTION

The vacuum assisted resin transfer molding (VARTM) process has been developed as a low cost method for the manufacture of composite structures. For many years, VARTM has been used to fabricate structural composites for the marine, military and infrastructure industries. Recent investigations have shown that it is possible to fabricate aircraft-quality composite structures by the VARTM process (1). However, it has been well documented that resin infiltration of advanced fiber architecture, high fiber volume preforms is a complex process and often dry or unimpregnated areas can occur in the preform. In addition, it is difficult to control the final fiber volume fraction and void content of the composite. Due to the complex nature of the VARTM process, trial and error methods of process development are inefficient and expensive.

A comprehensive simulation model of the VARTM composite manufacturing process has been developed. For isothermal resin infiltration, the model incorporates three submodels. These include submodels describing the viscosity and cure kinetics of the resin, resin flow through a porous reinforcement preform and compaction of the preform during the infiltration procedure. The accuracy of the model was validated by measuring the flow patterns, resin pressure and thickness changes during resin infiltration of flat preforms. In the present work, the modeling software was used to evaluate the effects of the distribution medium on resin infiltration of a flat preform. Different distribution medium configurations were examined using the model and the results were compared with data collected during resin infiltration of a carbon fabric preform.

2. VARTM MODEL FORMULATION

The VARTM process consists of two important mechanisms: flow of the resin through the preform, and compaction and relaxation of the preform under the vacuum pressure. In addition, the resin cure kinetics and viscosity must be known to ensure complete resin infiltration of the preform before resin gelation. A comprehensive simulation model consists of three coupled submodels: the resin flow in the preform, the compaction of the preform during the infiltration procedure, and the viscosity and cure kinetics of the resin.

2.1 Flow Model The flow model is used to calculate the flow of the resin through the distribution medium and the preform. Both the high-permeable distribution medium and the preform can be modeled as heterogeneous and anisotropic porous media. The resin fluid is assumed to be Newtonian and incompressible. Assuming that the flow is quasi-steady-state, the governing equations for the flow problem are the continuity equation for an incompressible fluid,

$$\nabla \cdot \vec{v} = 0 \quad [1]$$

and Darcy's law for flow through porous media (2),

$$\vec{v} = \frac{\vec{q}}{\phi} = \frac{S}{\mu} \nabla P_r \quad [2]$$

where, \vec{v} is the interstitial velocity vector of the resin, \vec{q} the superficial velocity vector, ϕ the porosity of the porous preform, μ the viscosity of the resin, S the permeability tensor of the preform, and P_r is the resin pressure.

The boundary conditions necessary to solve the governing equations are:

- A flow front pressure condition: $P_{r_{flow\ front}} = 0$
- A constant pressure condition at the inlet: $P_{r_{inlet}} = \hat{P}_r$
- The velocity normal to the mold wall and vacuum bag is zero: $\vec{v} \cdot \vec{n} = 0$, where \vec{n} is the vector normal to the boundary wall.

Infiltration of resin into the porous preform is a moving boundary problem. The finite element/control volume (FE/CV) method (3) is used to track the progression of the flow front. At each time step, the Galerkin finite element method is used to solve for the pressure distribution in the fluid. The resin velocities are then calculated using equation [2]. Once the resin velocities are known, the flow front location at that time is determined by the control volume technique.

2.2 Compaction Model Due to the flexible nature of the vacuum bag, there is no direct control over the thickness or fiber volume fraction of the composite part in the VARTM procedure. The compaction of the reinforcement preform is complex and depends on the compressibility and relaxation of the reinforcement under pressure, and the interaction between the reinforcement and the resin flow. Researchers (4,5) have conducted experiments to investigate compaction behavior of the preform during the VARTM process. The flexible nature of the vacuum bag allows pressure variations inside the mold cavity which resulted in laminates with a nonuniform final thickness. Rigas, et.al. (4) investigated variations of the final thickness in composite parts manufactured by the VARTM process. It was found that the final cured thickness of a part changes along the resin progression direction. As the distance from the vacuum source increases, the part thickness increases, and correspondingly, the fiber volume fraction of the laminates decrease.

It is well accepted that during resin infiltration of the preform, the total compaction pressure is shared by the resin pressure and the pressure supported by the fiber network (6,7). Therefore, equation [3] is introduced to account for the transverse equilibrium inside the mold cavity during impregnation (8):

$$P = P_r + P_n \quad [3]$$

where, P is the total compaction pressure ($\approx 1 \text{ atm}$), P_r is the resin pressure, and P_n is the net pressure applied on the preform.

At each time step, the resin pressure distribution is first calculated using the flow model and the net pressure applied on the preform is computed using equation [3]. The normal strain in the transverse direction, ϵ , can be obtained from curves of strain versus compression pressure, which are commonly obtained from compaction experiments on the preform. With the initial fiber volume fraction of the preform (V_{f_0}) and thickness of the panel (t_0) given, the displacement (w), thickness (t) and fiber volume fraction (V_f) can be calculated by the equations [4] – [6], respectively.

$$w = \int_0^t \epsilon ds \quad [4]$$

$$t = t_0 + w \quad [5]$$

$$V_f = V_{f_0} \frac{t_0}{t} \quad [6]$$

The relationship between the compressive strain in the preform and the applied pressure is obtained by fitting the compaction test results to an empirical model. Pressure versus strain data for a SAERTEX[®] multi-axial warp-knit (MAWK) carbon fiber fabric is shown in Figure 1. Two important phenomena are observed during the compaction experiments. First, because of the resin lubrication effect, the wet fiber sample saturated with resin is compacted more than the dry reinforcement under the same pressure. Second, the compressive response of the preform under the compaction force is not elastic, and the hysteresis occurs during unloading process (4,9).

During the VARTM infusion process, before the resin front approaches, the dry reinforcement is under vacuum compression. Thus, the compressive strain of the preform can be calculated from the compaction response of the dry preform during the loading process. As the resin is wetting the preform, the local net pressure applied to the preform decreases as a result of the increasing resin pressure. This is equivalent to unloading the preform. Accordingly, the strain in the wet preform is determined by the compaction response during unloading of a preform saturated with resin. Therefore, the compressive strain varies with the net pressure applied to the preform in the form of equation [7].

$$\epsilon = \begin{cases} f_1(P_n) & \text{dry compaction, loading} \\ f_2(P_n) & \text{wet compaction, unloading} \end{cases} \quad [7]$$

2.3 Resin Model The VARTM process uses mostly thermosetting polymeric resins. As the process progresses, the resin begins to cure and change viscosity. The VARTM fabrication method is often used to manufacture large structures that require long processing times, and the completion of the impregnation process before resin gelation becomes a major challenge. Therefore, a model is necessary to predict the cure and viscosity change of the resin.

A typical expression for the cure kinetics model is given as follows

$$\frac{d\alpha}{dt} = f_k(T, \alpha)(1 - \alpha)^n \quad [8]$$

where, $d\alpha/dt$ is defined as the reaction or cure rate, α the degree of cure, T the resin temperature, $f_k(T, \alpha)$ a function that depends on the reaction type, and n is the reaction order. The cure rate is a function of resin temperature and degree of cure. Differential scanning calorimetry is a common method used to develop the kinetic model.

If diffusion of chemical species and convection of the fluid is neglected, the degree of cure at each point inside the material can be determined by integrating the expression for the cure rate with respect to time in the following manner:

$$\alpha = \int_0^t \frac{d\alpha}{dt} dt \quad [9]$$

To accurately predict the resin infiltration process, the viscosity of the resin must be known as a function of both position and time. Resin viscosity is a complex function of shear rate, degree of cure and temperature. The approach that is commonly used is to assume that the resin is a Newtonian fluid. The resin viscosity is measured as a function of time and temperature and the kinetics model in equations [8] and [9] is used to calculate the degree of cure as a function of time. The viscosity data are fit to a mathematical expression relating temperature and degree of cure to the viscosity,

$$\mu = \mu_o(T) f_k(\alpha) \quad [10]$$

where μ is the viscosity and μ_o and f_k are functions that account for the effects of temperature and cure on viscosity, respectively.

3. VARTM SIMULATIONS

In the present investigation, the process simulation model was used to investigate resin infiltration during VARTM fabrication of composite panels. For the simulations, the properties of SAERTEX[®] multi-axial warp-knit (MAWK) carbon fiber fabric were used for the preform and A.T.A.R.D. Laboratories SI-ZG-5A epoxy were used for the resin. The MAWK fabric was composed of seven plies of both AS-4 and IM-7 carbon fibers. The plies are laid up in a [45,-45,0,90,0,-45,45] stacking sequence and knitted together with a polyester thread. To assess the accuracy of the model, the predicted flow patterns and the changes in resin pressure and preform thickness during the infiltration procedure were compared with the values measured during infiltration of the preform by the VARTM process.

3.1 Material Characterizations Compaction tests were conducted to determine the compressive response of the MAWK fabric during VARTM processing. The experimental procedures are given in references 9 and 10. Both dry and wet compaction tests were performed. For the wet preform test, the preform was initially impregnated with SI-ZG-5A resin.

Empirical equations of preform strain as a function of pressure for unstitched MAWK fabric are obtained by fitting the compaction test data to the mathematical expression shown in equation [11] for a seven ply stack of fabric:

$$\epsilon = \begin{cases} 0.22(1 - \exp(-0.026P_n)) & \text{dry compaction, loading} \\ 0.028 + 0.20 \frac{P_n}{1.87 + P_n} & \text{wet compaction, unloading} \end{cases} \quad [11]$$

where, ϵ is the strain of the preform and P_n is the pressure applied to the preform.

The permeability of the SAERTEX[®] Multi-Axial Warp Knit (MAWK) carbon preform was measured in the three mutually perpendicular principal material directions. These directions are in-plane along knitting, in-plane normal to knitting, and through the thickness (TTT) direction. The experimental procedures are described in detail in references 9 and 10. The power law equation was chosen to fit the permeability data as a function of the fiber volume fraction:

$$S_{ij} = a(V_f)^b \quad [12]$$

where, S_{ij} is the permeability in m^2 , V_f is the fiber volume fraction, and a and b are fit constants. The fit constants are presented in Table 1.

Table 1. Permeability constants for SAERTEX[®] preform.

	a	b
In-plane along knitting	2.0×10^{-13}	-7.62
In-plane normal to knitting	4.0×10^{-13}	-5.36
Through thickness	6.0×10^{-15}	-7.29

The distribution medium used in this study contains three layers of nylon mesh screen. The nylon screen is in-plane isotropic. The in-plane and transverse permeabilities of the distribution medium were measured to be $8.31 \times 10^{-9} m^2$ and $5.49 \times 10^{-10} m^2$, respectively. The porosity of the distribution medium is 0.75.

SI-ZG-5A epoxy resin is a commercially available anhydride-cure epoxy blend developed for the VARTM process at A.T.A.R.D laboratories. It features low viscosity at room temperature, which is essential for the VARTM process due to the low injection pressure.

The cure kinetics model for SI-ZG-5A was obtained using isothermal and dynamic differential scanning calorimeter (DSC). A modified auto-catalytic equation was chosen to model the curing reaction for the resin. A Rheometric Ares System-Five Parallel-Plate Rheometer was used to measure the resin viscosity. The resin viscosity was found to fit to an equation of the form given in equation [10]. Details of the DSC and rheometry experiments along with the procedures used to fit the data to the mathematical equations are given in Grimsley, et.al. (11).

For the present study, the resin injection experiments were performed at room temperature and the total infiltration times were around 5 minutes. At room temperature, the viscosity of SI-ZG-5A is 0.34 Pa_s and increases only by 5% after 100 minutes. A constant viscosity of 0.34 Pa_s was used in the VARTM simulations of the flat preforms described in the next section.

3.2 Experiments Flat panels (60.96 cm by 30.48 cm) were fabricated by the VARTM process using SAERTEX multi-axial warp knit carbon fiber fabric and the SI-ZG-5A epoxy resin [9]. The panel contained one stack of the fabric and the initial preform thickness was 0.19 cm.

A 1.27 cm thick aluminum tool was instrumented to allow for measurement of pressure and displacement of the preform during the VARTM infiltration. The pressure sensors and Linear Variable Displacement Transducers (LVDT) were installed to monitor the pressure and thickness change of the panels at different locations (see Figure 2). The pressure sensors, labeled P1 through P3 were mounted at the tool surface beneath the fiber preform. P1 was 2.5 cm from the preform edge on the resin inlet side, P2 was at the center of the preform, and P3 was 2.5 cm from the preform edge on the vacuum side. LVDTs, labeled D1 through D3, were supported above the vacuum bagged preform by a rigid beam. D1 was 3.9 cm from the preform edge on the resin inlet side, D2 was at the center of the preform, and D3 was 3.9 cm from the preform edge on the vacuum side. The preform was cut and placed on the tool. A layer of Armalon fabric was placed above the preform to serve as the release film. The distribution medium was laid on top of the preform and release layer. The medium was cut smaller than the preform allowing a 1.27 cm gap between the edge of the medium and the edge of the preform along the length. The distribution medium ended at a distance of 2.54 cm before the end of the preform. These gaps prevent race-tracking of the resin as it flows through the media and the preform. A 5.08 cm portion of the medium was set off of the panel at the inlet side for inlet tube placement (Figure 2). The outlet tube located on the vacuum side of the part was connected to a resin trap and vacuum pump. The bagging procedure was completed when the preform, medium and tubing were sealed to the aluminum tool using a conformable vacuum bag and sealant tape.

SI-ZG-5A resin was degassed at room temperature under full vacuum for approximately one hour prior to injection. Once the system was equilibrated and all air leaks were eliminated, the resin was allowed to flow into the distribution medium and fiber preform. The flow front at the top surface of the part was recorded using a digital video camcorder. The bottom flow front position was obtained from the tool mounted pressure sensor responses recorded during the test. Typically, the presence of the flow front at the tool surface is indicated by a decrease in the vacuum measured by the sensor. When the preform was fully impregnated, as evidenced through visual inspection, the inlet and then the outlet tube were clamped. The part was then placed in an oven to cure.

3.3 Simulation Results For the flat panels investigated in this study, resin flow is uniform across the width of the panels, except at the edges where there is no distribution medium. Hence, the resin velocity in the width direction is negligible and the resin infiltration of the flat preform can be modeled as a two-dimensional flow problem.

The simulation model was used to evaluate the correct way to model the distribution medium. Three different distribution medium configurations were investigated. In Model I (Figure 3), it is

assumed that the distribution medium fits tightly against the left edge of the preform. The boundary conditions in the model are set up to allow resin flow into the preform from above, through the top surface, and from the left edge. However, in the experimental program discussed in the previous section, no special efforts were made to ensure that the distribution medium was in contact with the edge of the preform. In the second model (Model II, Figure 3), the distribution medium was detached from the left edge of the preform and the boundary conditions were specified to allow resin infiltration from the top surface only. Both Models I and II accurately model how the distribution medium drapes off the left edge of the preform and the placement of the resin injection tube. The third model is a simplified version of Models I and II where the injection tube is placed directly on top of the distribution medium at the left edge of the preform (Model III, Figure 3). The results of the three simulations were compared with resin infiltration data obtained from the experiments.

Shown in Figures 4 – 6 are comparisons between the calculated and measured flow front positions, at the top and bottom of the preform, for Models I – III, respectively. The simulation results of Model II agree with the data very well while Model I over predicts the infiltration time by approximately 1.7 times. This validates the assumption of Model II that the distribution medium did not conform to the shape of the preform at the left end and resin enters through the top of the preform. In Figure 5, it was observed that the flow front in the highly permeable distribution medium leads the resin front on the bottom surface of the preform. Once the resin exits the distribution medium, the top and bottom flow fronts slow significantly, and the bottom flow front catches up with the top resin front. This illustrates the importance of the distribution medium in reducing the infiltration time. Initially one might think that the infusion scheme depicted in Model I would shorten the infiltration time because the resin enters the preform through the distribution medium from above and the left edge simultaneously. However, the amount of resin entering the preform through the top is reduced (Q_1) due to the resin entering the left edge of (Q_2) as shown in Figure 7. This leads to a significant increase in the total infiltration time compared to the infusion scheme of Model II. The resin infusion scheme in Model III gave a reasonably good estimate of the resin infiltration process considering the simplicity of the model. The predicted resin infiltration was faster than measured in the experiment which is due to moving the resin inlet tube to the top of the preform.

4. CONCLUSIONS

A comprehensive Vacuum Assisted Resin Transfer Molding (VARTM) process simulation model was developed. The model incorporates resin flow through the preform, compaction and relaxation of the preform, and viscosity and cure kinetics of the resin. The computer model can analyze the resin flow details, track the thickness change of the preform, predict the total infiltration time and final fiber volume fraction of the parts, and determine whether the resin could completely infiltrate and uniformly wet out the preform. The modeling software was used to examine how the distribution medium and the position of the resin inlet tube effect the resin infiltration of a flat preform. Three different distribution medium and resin inlet tube configurations were evaluated using the model and the results were compared with data collected during resin infiltration of a carbon fabric preform. The results show how the distribution medium influences the resin infiltration process and that resin infiltration into the preform can be accurately predicted when the distribution medium is modeled correctly.

5. ACKNOWLEDGEMENTS

The work was supported by NASA Langley Research Center under Research Cooperative Agreement NCC-1-01037. The project monitor is Mr. Roberto J. Cano.

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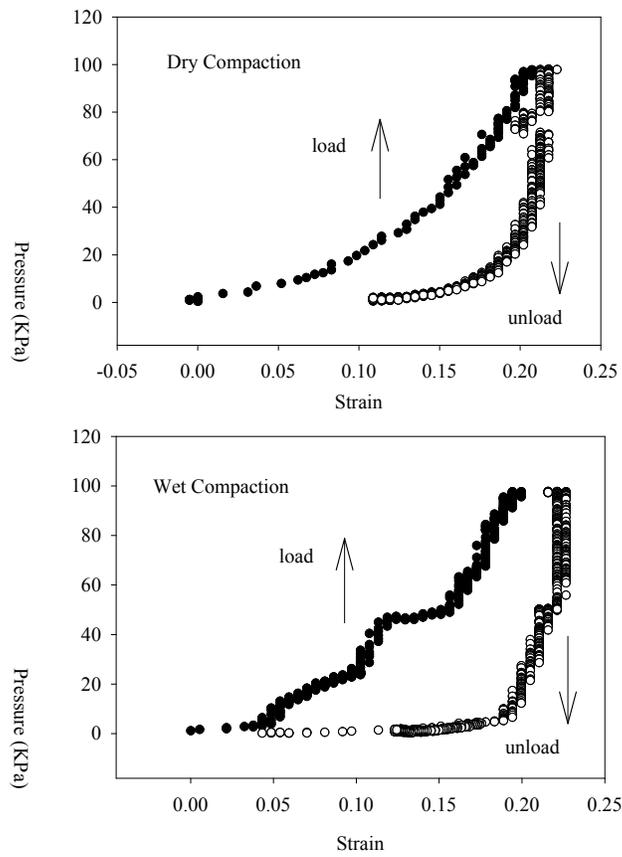


Figure 1. Compaction data for SAERTEX[®] carbon.

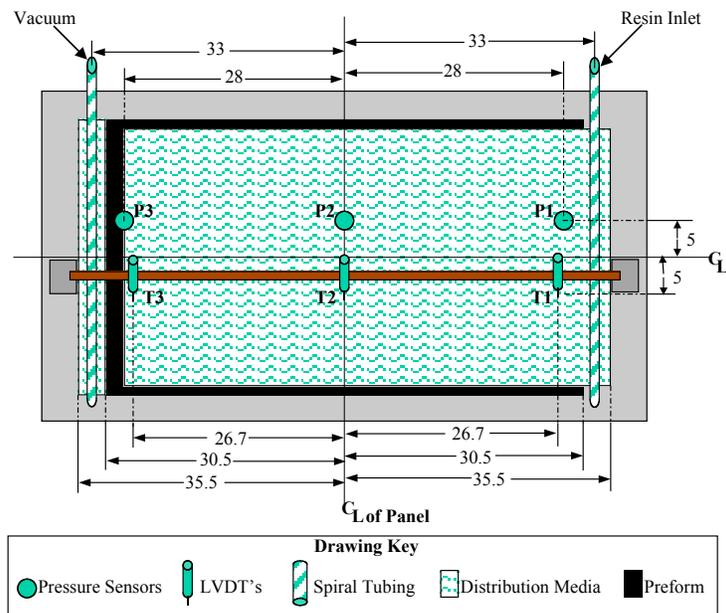
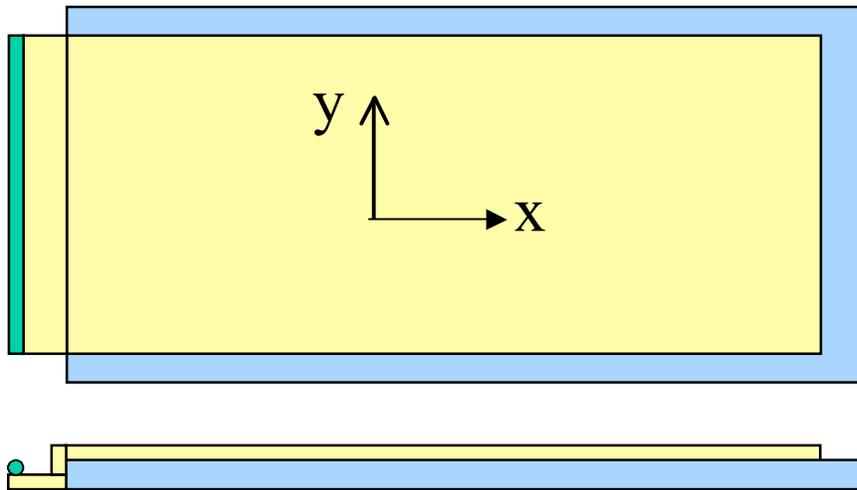
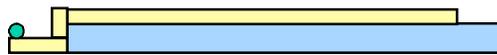


Figure 2. Instrumented VARTM tool.



● Resin inlet tube
 ■ Distribution fabric
 ■ Preform



Model I



Model II



Model III

Figure 3. VARTM infusion schemes.

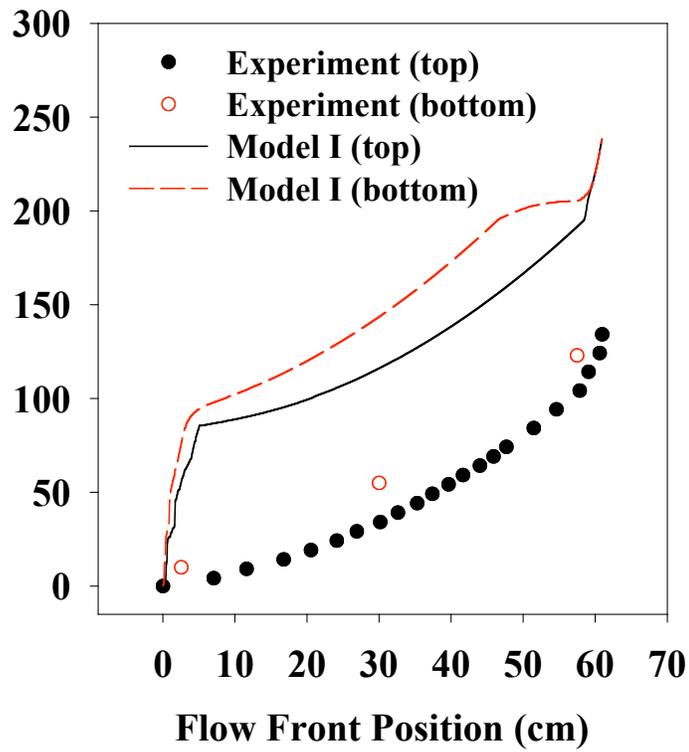


Figure 4. Comparison between measured and Model I predicted flow front position.

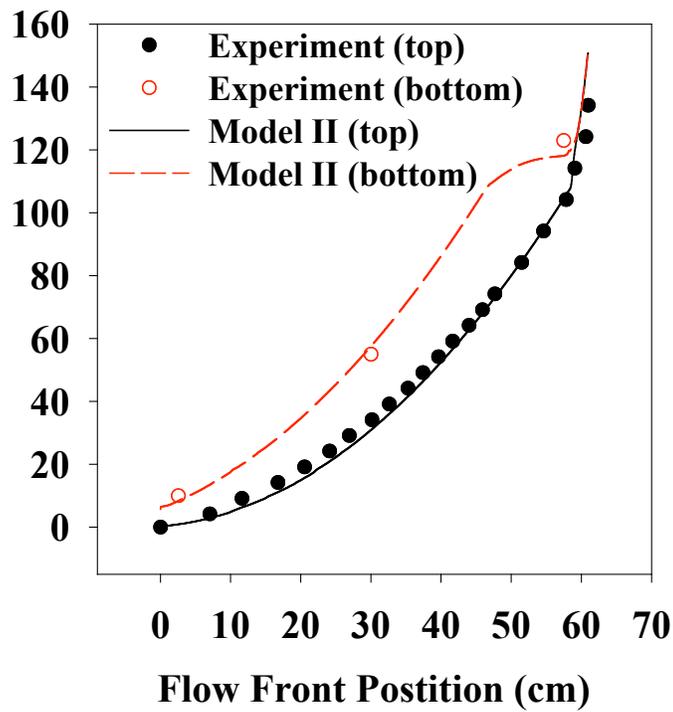


Figure 5. Comparison between measured and Model II predicted flow front position.

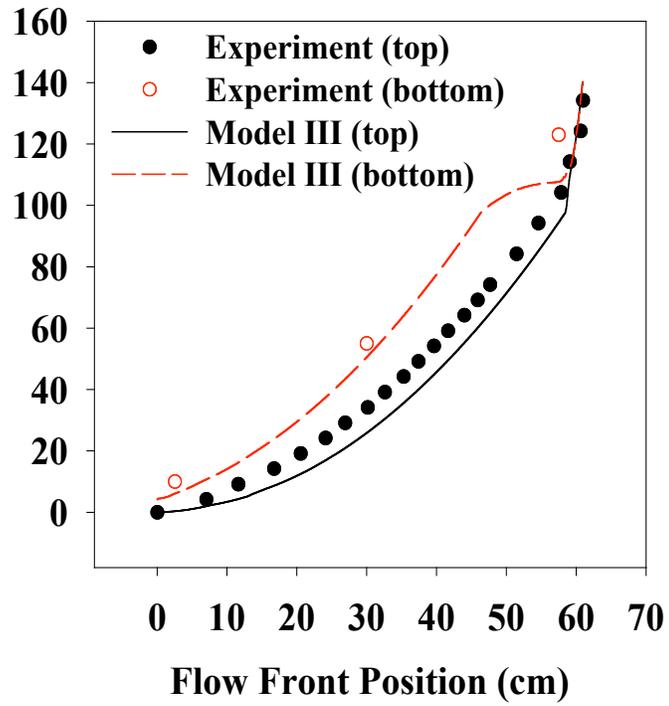


Figure 6. Comparison between measured and Model III predicted flow front position.

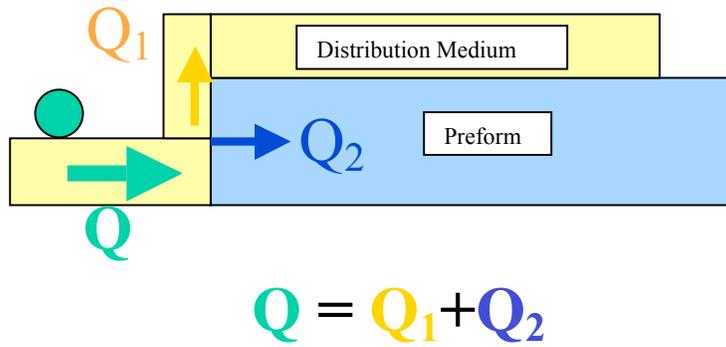


Figure 7. Resin flow in the distribution medium for Model I.